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Minimum fluidization velocity of ground chip and ground pellet particles of woody biomass

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ABSTRACT

The present work reports the hydrodynamic properties of ground chip (GC) and ground pellet (GP) particles of pine wood. Ground particles are made by grinding whole wood chips and whole wood pellets in a hammer mill equipped with a 3.2 mm screen. The average diameter of the particles measured by using image processing is 0.75 mm for GC particles and 1.31 mm for GP particles. The average density of particles is 1.33 g/cm^3 for GC and 1.43 g/cm^3 for GP. Pressure drop versus the air flow across a bed of particles is measured and the parameters of Ergun equation are estimated. GP particles have a minimum fluidization velocity of 15.2 cm/s which is much higher than the minimum fluidization velocity of GC particles at 8.5 cm/s. Both GC and GP particles undergo channeling and bed separation during fluidization. No bubbling regime was observed.

1. Introduction

Lignocellulosic biomass has a great importance in production of renewable fuels. Several biomass-based thermo-chemical conversion processes such as combustion, pyrolysis and gasification are under development [1]. Many of these technologies are based on fluidization technology [2]. Fluidization is a well-known engineering process by which a bed of particulate materials is made to behave as in a fluid-like regime. A fluidized bed achieves the highest heat transfer rate and the most efficient conversion [3,4]. Fluidization also occurs when biomass is pneumatically conveyed and fed to the combustion chambers in power generation plants. In these systems, biomass particles are pushed by the gas flow in a saltatory conveyance. To improve the thermal conversion efficiency and ease of particles' handling, literature recommends to reduce the size of biomass particles to smaller than 2 mm [5–12].

In a fluidized column, the particles become fluidized when an upward flowing gas imposes a high enough drag force to overcome the downward gravity force [13]. The drag force is the frictional force applied by the flowing gas on the particles [14]. Majority of the fundamental works on particulate processing are focused on spherical particles with a very narrow size distribution, whereas the biomass particles are often highly irregular in their shape [15]. The heterogeneous properties and irregular shape of biomass particles make the handling and processing of particles difficult. Behavior of biomass particles subjected to a gas phase in the fluidized beds and pneumatic transportation lines is not easily predictable and controllable. Various techniques such as baffles, pulsing flow and/or mechanical vibration are developed to aid the fluidization of biomass particles [16,17].

A wide range of minimum fluidization velocity values are reported for various bed mediums. The published values in the literature are seldom comparable even for the same material. Paudel [18] listed the published minimum fluidization velocity values for Walnut and pieces of corn cob. In some cases, there was a 300% difference in values due to the differences in size and shape characteristics of tested materials that are not well documented. The authors could not find a well-accepted equivalent particle size in the literature. For example, many published studies used sieving average particle size. It is well documented that particle size based on sieve analysis underestimates the real size and shape of particles [15], which consequently underestimates the predicted minimum fluidization velocity [18]. The review of published literature demonstrates that more experimental fluidization study along with a complete size and shape characterization of particles is required.

In a review of types of gas fluidization, Geldart [19] explained that size of the particles linearly increases the minimum fluidization velocity. Larger particles are heavier and have a greater projected area that raises the drag force. Thus, increasing the dimensions of particles requires higher gas flow rate proportionally [2,3,19–22]. Another important factor is the particle density. Cui and Grace [2] explained that density of particles directly changes the drag and gravitational forces leading to an increase in the minimum fluidization velocity. Geldart gas fluidization classification shows that a higher density of single and bulk

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Nomenclature

A	Blake-Kozeny-Garman constant
A_c	Cross-sectional area of bed, cm^2
Ar	Archimedis number
AR	Aspect ratio
B	Burke-Plummer constant
BER	Bed expansion ratio
d_{CI}	Inscribed circle diameter, mm
d_{CC}	Circumscribed circle diameter, mm
d_{eq}	Equivalent particle diameter, mm
d_p	Particle characteristic length, mm
d_{sv}	Sieving mean particle size, mm
H	Instantaneous bed height, cm
H_i	Initial bed height, cm
L	Particle length, mm
M	Overall mass of bed, g
Re	Reynolds number
U_g	Superficial gas velocity, cm/s
U_{mf}	Minimum fluidization velocity, cm/s
W	Particle width, mm

Greek symbol

ΔP	Pressure drop, Pa
ε	Bed porosity
ρ_b	Bulk density, g/cm^3
ρ_g	Gas density, g/cm^3
ρ_p	Particle density, g/cm^3
μ_g	Gas viscosity, Pa s
Ψ	Sphericity

of particles exhibits a better quality and more stable fluidization [2,19]. Chip and pellet are two forms of the woody feedstock available in the market. Pellets are produced from compacting saw dust. Wood pellet provides a convenient form of biomass for its handling, storage and feeding to the conversion reactors [23,24]. Pelletized biomass is denser, has a higher bulk density, has more homogenous physical properties and has enhanced flow properties than un-processed wood chip [11,25,26]. Rezaei et al. [15] showed that pelletization modifies the shape of particles from long and thin to irregular-round.

The minimum fluidization velocity is one of the most important design parameters of a given gas-solid system [2,27]. The minimum fluidization velocity depends upon size, shape and density of particles. The ground woody particles are inherently irregular in shape and size and thus their fluidization behavior is expected to be difficult to predict.

To the knowledge of the authors, there is very limited information on comparing the fluidization characteristics of ground chip (GC) and ground pellet (GP) particles. The objective of the current study is to understand the influence of particle density and shape on the hydrodynamic properties of particles subjected to a gas phase flow. In a previous work [15], the flowability of GC and GP particles were evaluated. The current paper characterizes fluidization behavior of GC and GP particles vs. size, density and shape of the particles. Fluidization is characterized by hydrodynamic properties of particles such as pressure drop, minimum fluidization velocity and bed expansion ratio in a cold fluidized bed apparatus. The output experimental and modeling results help to have a better understanding on the fluidization behavior of biomass particles in combustion applications.

2. Material and methods

2.1. Materials

Pine wood chips (30 × 30 × 5 mm) and commercially produced pine wood pellets (diameter of 6 mm and lengths of 12–24 mm) are supplied by Fiberco, a wood chip and pellet handling and shipping operation in North Vancouver, BC, Canada. Upon their arrival at the lab, the pine chips are dried down to 4–5% moisture content in a THELCO laboratory PRECISION oven (Thermo Electron Corporation, Model 6550) at 80 °C. After cooling, the dried chips are crushed in a hammer mill (Glen mills Inc., USA; Model 10HMBL) equipped with a screen 3.2 mm circular holes. The pellets as received have a moisture content of 5–6% and thus are not subjected to oven drying. Wood pellets are ground using the same hammer mill and screen size. Fig. 1 shows the wood chips, wood pellet, ground wood chip particles and ground wood pellet particles.

2.2. Particles characterization

2.2.1. Particle size distribution

Particle size distribution are determined using mechanical sieving and laser diffraction techniques. The procedure outlined in ASABE ANSI Standard S319.3 is followed by using a tap sieve shaker (Ro-Tap RX 94) with a stack of sieves of 0.25, 0.5, 1.0, 1.4, 2.0 and 2.8 mm perforations. The shaker subjects the samples to oscillation and tapping for 10 min. The mass-averaged diameter of particles is calculated using Eq. (1) [28].

$$d_{sv} = \frac{1}{\sum x_i/d_i} \quad (1)$$

where x_i is the retained mass fraction of particles in the i^{th} interval of mean diameter (d_i) between two sieves.

2.2.2. Particle shape analysis

A representative number of particles are randomly picked from each sample and pictured using a microscope. Pictures are thresholded and analyzed using an image processing software (ImageJ ver. 1.49 h, National Institutes of Health, USA). The full procedure of sample taking and image analysis procedure of single particles are explained in the previous study [15]. Fig. 2 also illustrates the various dimensions of each single particles.

The width and length of single particles are measured using the ellipse fitting technique. The aspect ratio of particles is measured using Eq. (2).

$$AR = W/L \quad (2)$$

where W (mm) and L (mm) are particles' width and length, respectively. The full procedure of thresholding and measurement of particles' dimensions is explained extensively in the previous work [15].

Owing to difficulty in measuring the surface area and volume of irregular-shape particles, a two-dimensional equivalent spherical diameter (d_{eq}) is suggested by Biagini et al. [29].

$$d_{eq} = (L \times W^2)^{1/3} \quad (3)$$

Sphericity (Ψ) of a particle indicates how closely the particle's shape looks like a sphere. Sphericity is defined as surface area of a sphere having the same volume of the particle divided by the actual surface area of the particle [30,31]. A quicker method is proposed based on the two dimensional measurements of inscribed circle diameter (d_{CI}) and circumscribed circle diameter (d_{CC}) [32]. Inscribed circle is the largest circle that fits inside the particle's boundary. Circumscribed circle is smallest circle that encloses the particle's boundary. This technique determines the sphericity, as expressed in Eq. (4) [28].